

# **LES of high-Reynolds-number Coanda flow separating from a rounded trailing edge of a circulation control airfoil**

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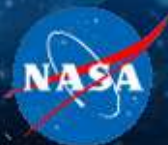
- Circulation control airfoil
- Separation of turbulent Coanda flow ~ *A major difficulty in RANS* ~

## 2. Details of the computations

## 3. Results

- LES results
- Comparisons between LES and RANS

## 4. Conclusions



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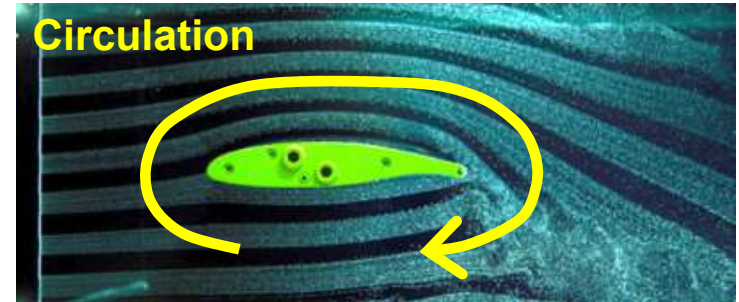
# Introduction: Circulation Control (CC) airfoil

~ For the next generation of passenger aircraft ~

## Circulation control by “Coanda jet”

Jet flow attaches on a rounded trailing edge of an airfoil

- Circulation is increased
- Lift is enhanced



Hydrogen bubble flow visualization of a CC airfoil (NASA LaRC, 2002)

## CC for Aircraft applications

- Lift enhancement (by single jet-blowing)
- Maneuver support (by dual jet-blowing)

### **Coanda effect:**

*The tendency of a fluid jet to stay attached to an adjacent curved wall, named after Henri Coanda*



Concept image of hybrid-wing-body aircraft employing CC devices



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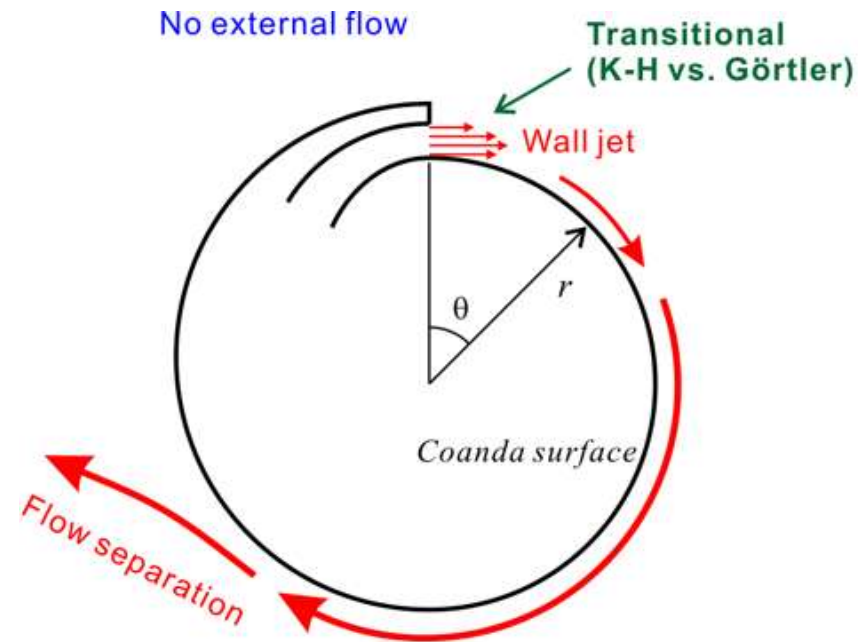
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# Introduction: Separation of turbulent Coanda flow

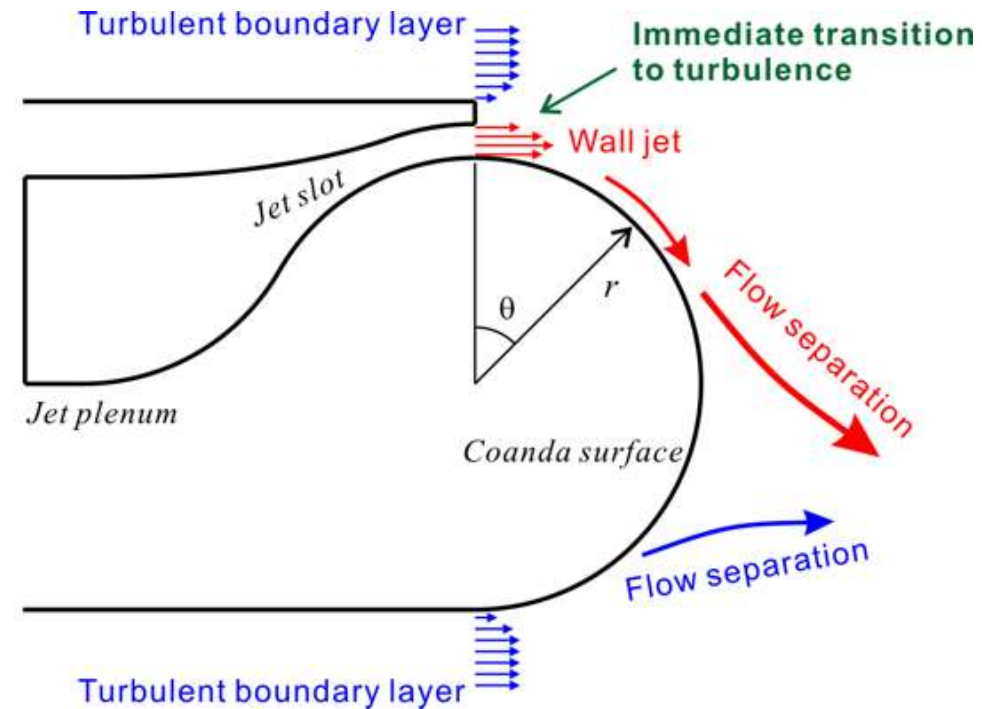
~ A major difficulty in current RANS Simulations ~

## Coanda jet over a cylinder (Exp. by Wygnanski et al.)



Jet flow characteristics are sensitive to the transition process

## Coanda jet over a rounded trailing Edge of a CC airfoil



Jet flow develops to fully turbulent at the jet exit



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# Objectives of the study

1. To investigate detailed physics (flow structures and statistics) of the fully turbulent Coanda jet applied to a CC airfoil, by using LES
2. To compare LES and RANS results to figure out how to improve the performance of existing RANS models for this type of flow

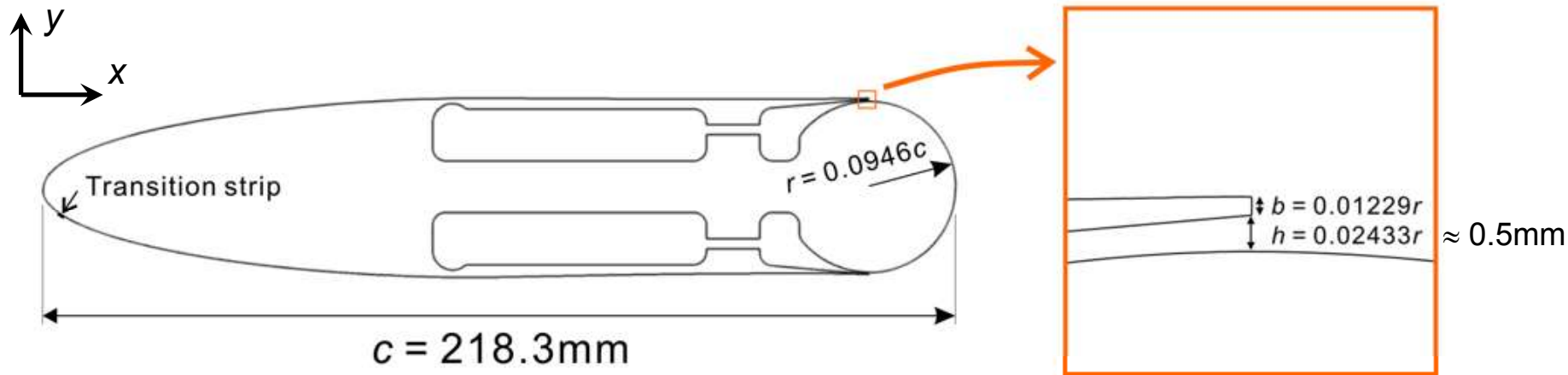


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# Airfoil configuration



- 20%-thick, non-cambered, elliptic-leading-edge CC airfoil  
(designed by Dr. Englar's research group at GTRI – currently tested at NASA Langley)
- Two independent jet plenums for the upper and lower sides  
(lower jet slot is closed in this study – may be used for “dual blowing” in future studies)
- Chord Reynolds number: 0.49 million
- Wavy transition strip attached near the leading edge



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# Numerical methods (LES)

## **Incompressible Navier-Stokes solver “CDP”**

(developed at the Center for Turbulence Research, Stanford University)

- Unstructured, finite-volume solver
- Energy-conservative, 2nd-order central difference scheme
- Fully-implicit, 2nd-order time integration scheme
- Dynamic Smagorinsky model for the subgrid-scale (SGS) stresses
- Running on massively parallel supercomputers (256 CPU's used)

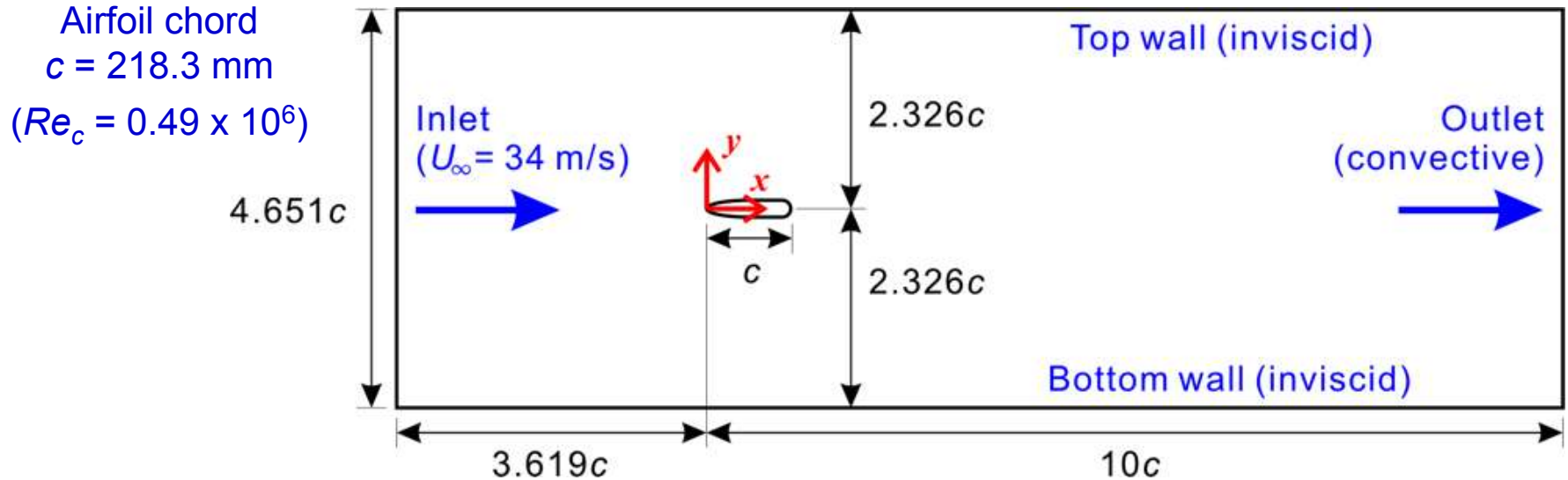


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# Computational domain & Boundary conditions



Wind tunnel geometry: NASA Langley Basic Aerodynamics Research Tunnel (BART)

Spanwise (periodic) domain size:  $14 \text{ mm} = 0.0641c = 27.8h$

- The domain wide enough to study turbulent structures in the Coanda jet
- 3D RANS study has shown little sidewall effects at low jet-blowing case



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# Jet blowing conditions (at the jet exit)

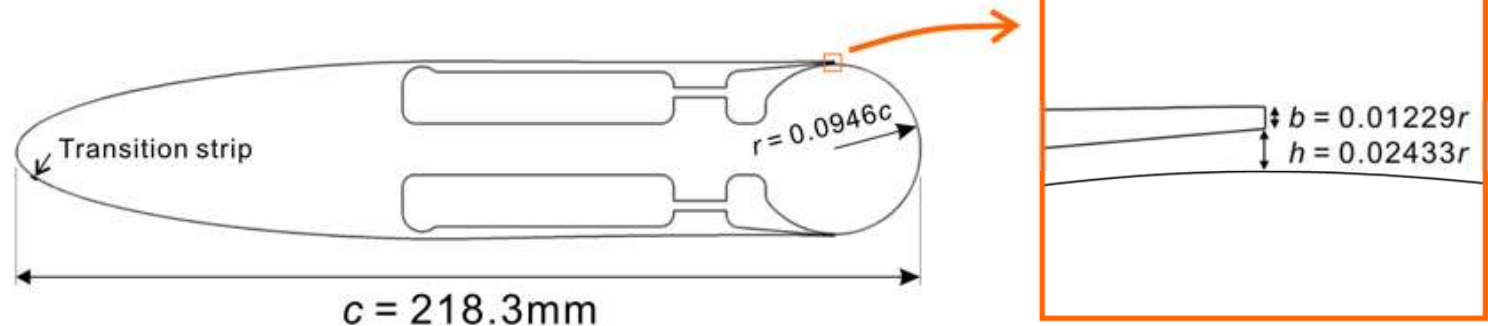
Jet-blowing rate	$U_j$ [m/s]	$U_{j,\max}$ [m/s]	$Re_j$	$C_\mu$
<b>Low</b>	105.3	$\approx 135$	$\approx 4500$	0.044
<b>High</b>	173.4	$\approx 216$	$\approx 7200$	0.120

$U_j$  : Bulk jet velocity (mean of the time-averaged velocity profile)

$U_{j,\max}$  : Maximum jet velocity (maximum of the time-averaged velocity profile)

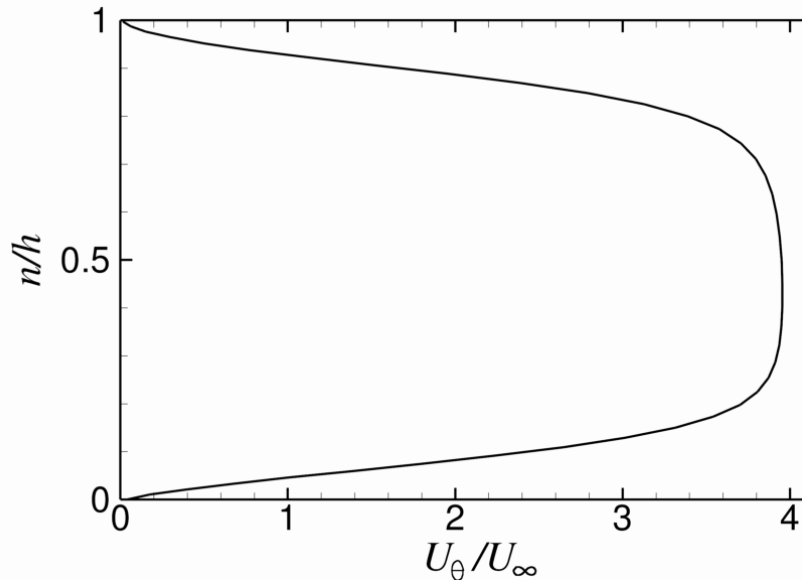
$Re_j$  : Jet Reynolds number ( =  $U_{j,\max} h / \nu$  )

$C_\mu$  : Jet momentum coefficient ( =  $2U_j^2 h / U_\infty^2 c$  )

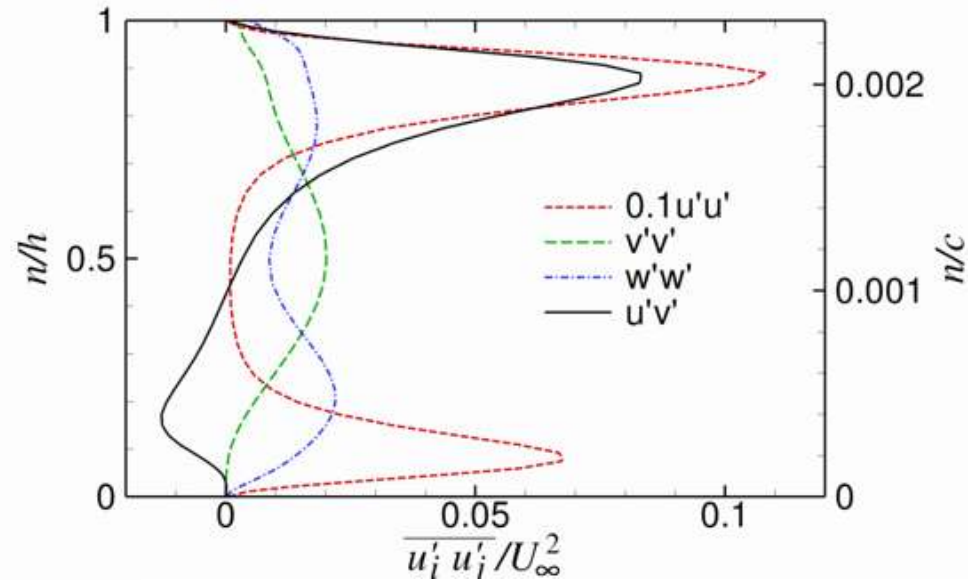


# Mean flow profiles (at the jet exit)

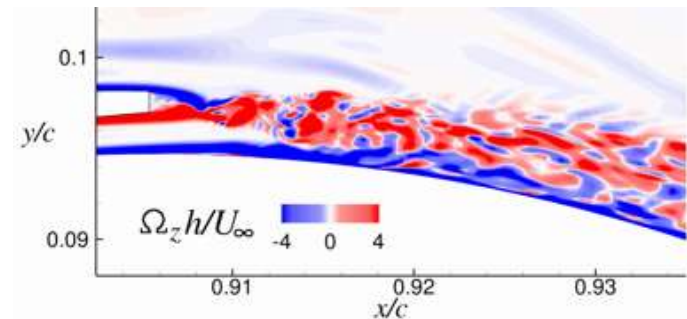
## Streamwise velocity



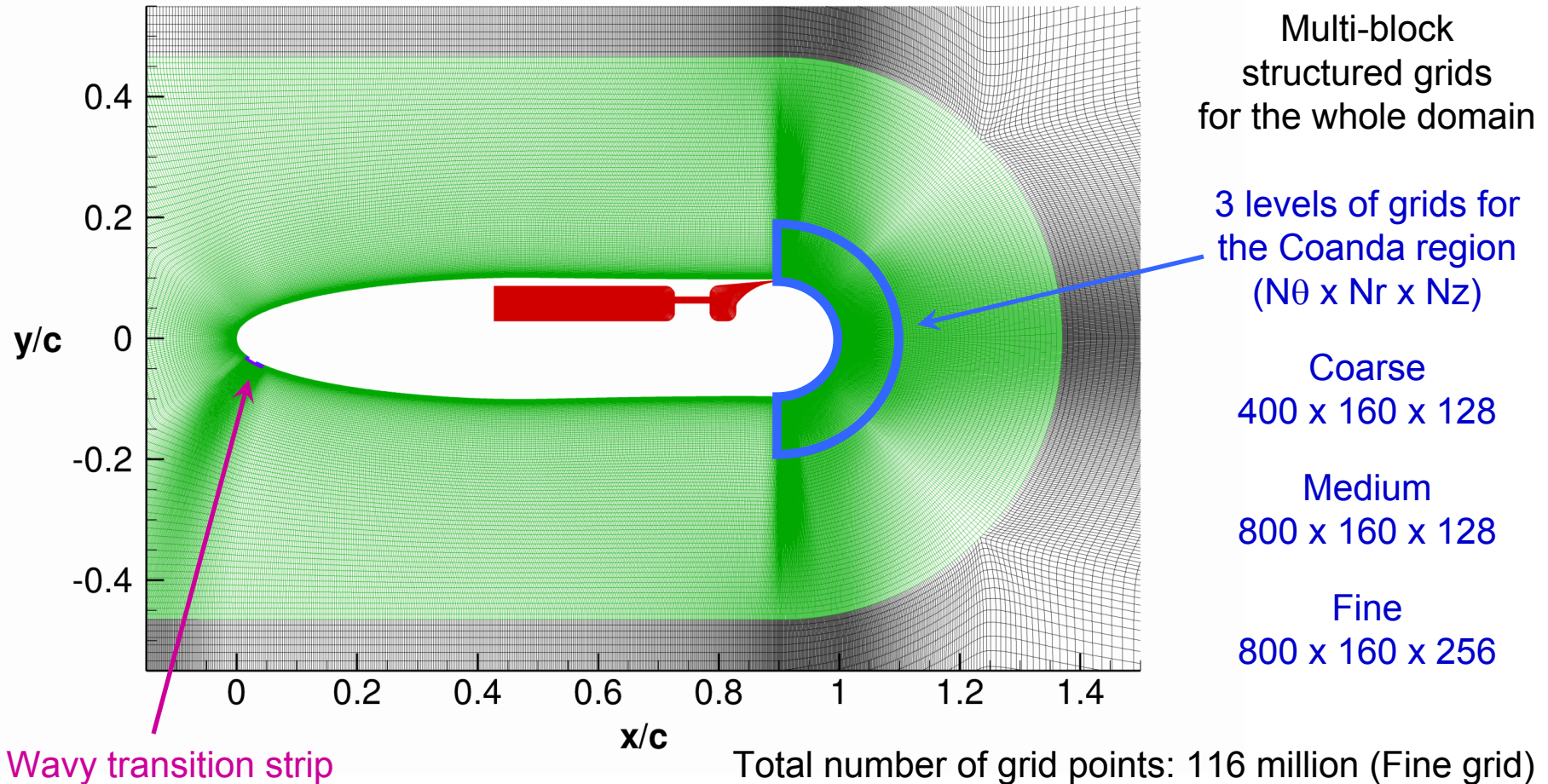
## Reynolds stresses



Jet oscillating due to alternating (von Kármán type) vortex shedding behind the thin jet blade



# Computational grids



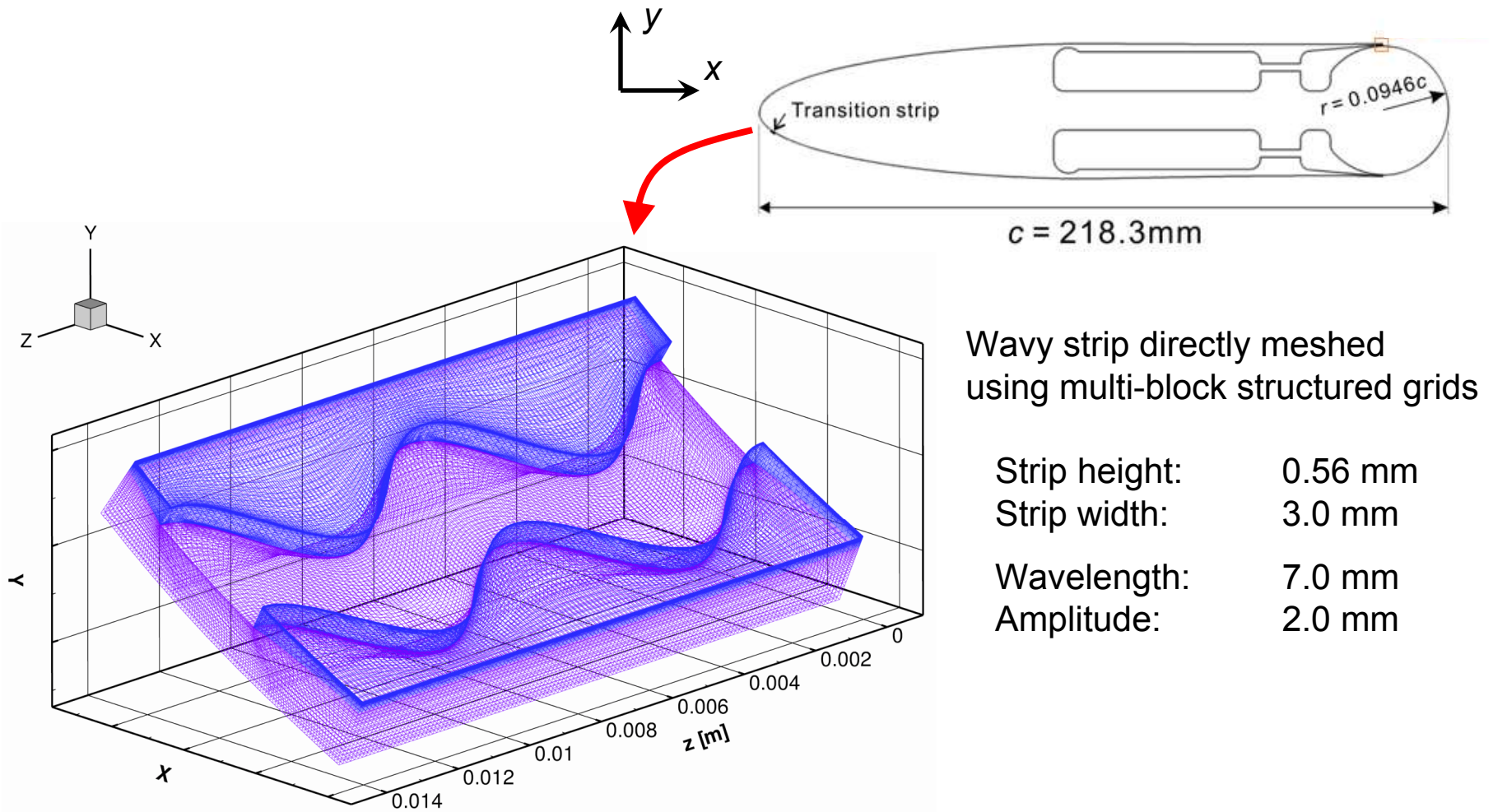
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# Wavy transition strip



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# Grid resolution (Fine grid)

Coanda surface	Resolution [mm]	Resolution in wall units		
	( $\theta = 10^\circ \sim 170^\circ$ )	( $\theta = 15^\circ$ )	( $\theta = 30^\circ$ )	( $\theta = 45^\circ$ )
Chordwise	0.0902	$\approx 95$	$\approx 65$	$\approx 30$
Wall-normal	0.00127	$\approx 1.4$	$\approx 1.0$	$\approx 0.5$
Spanwise	0.0547	$\approx 55$	$\approx 40$	$\approx 18$

Airfoil surface	Resolution [mm]	Resolution in wall units	
	( $x/c = 0.5$ )	(upper, $x/c = 0.5$ )	(lower, $x/c = 0.5$ )
Chordwise	0.4906	$\approx 70$	$\approx 45$
Wall-normal	0.00254	$\approx 0.4$	$\approx 0.25$
Spanwise	0.0547	$\approx 7.5$	$\approx 5.0$

SGS eddy viscosity: Up to about 5 times larger than the molecular viscosity  $\mu$  (just downstream of the jet exit, where RANS eddy viscosity is about 40 to 50  $\mu$ )



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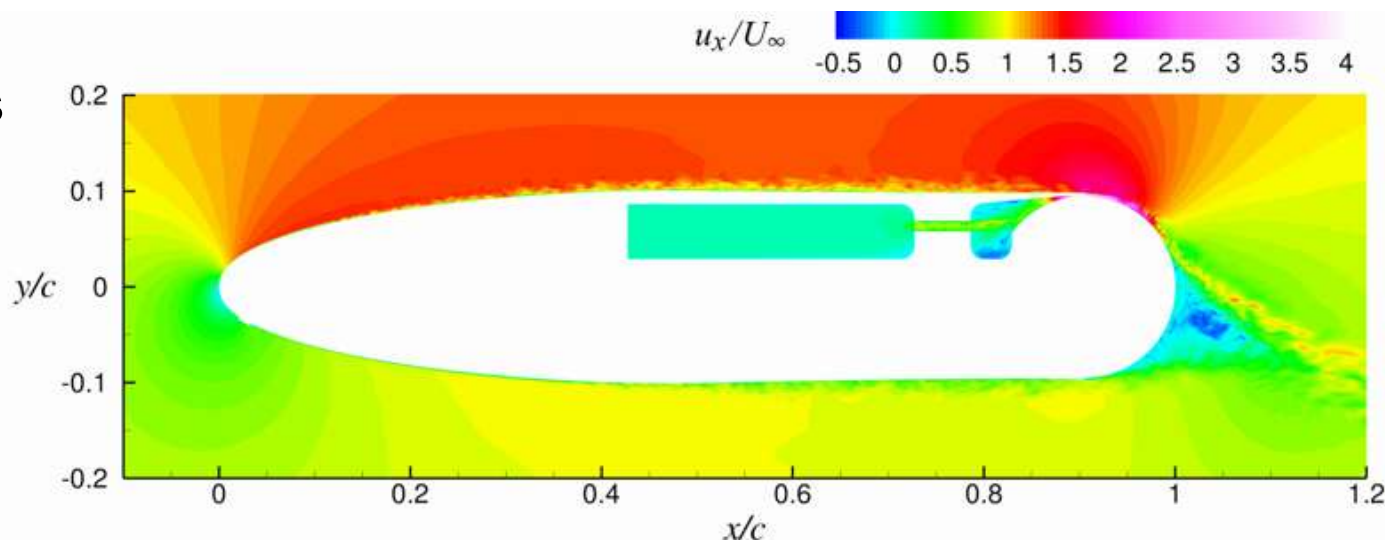
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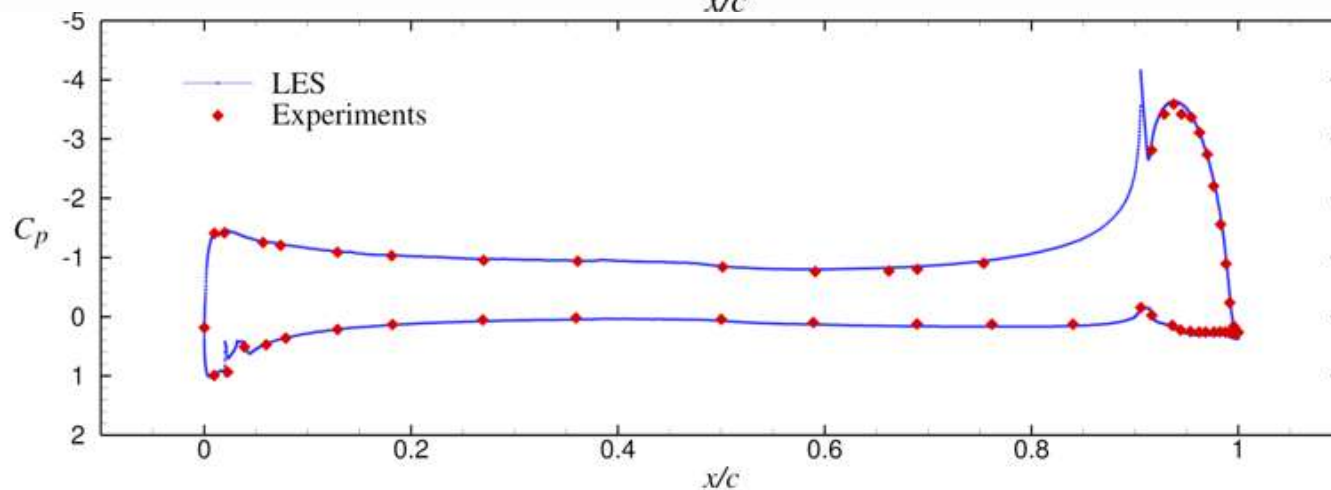


# LES results: Flow around the airfoil

Instantaneous  
streamwise  
velocity



Time-averaged  
pressure  
coefficient



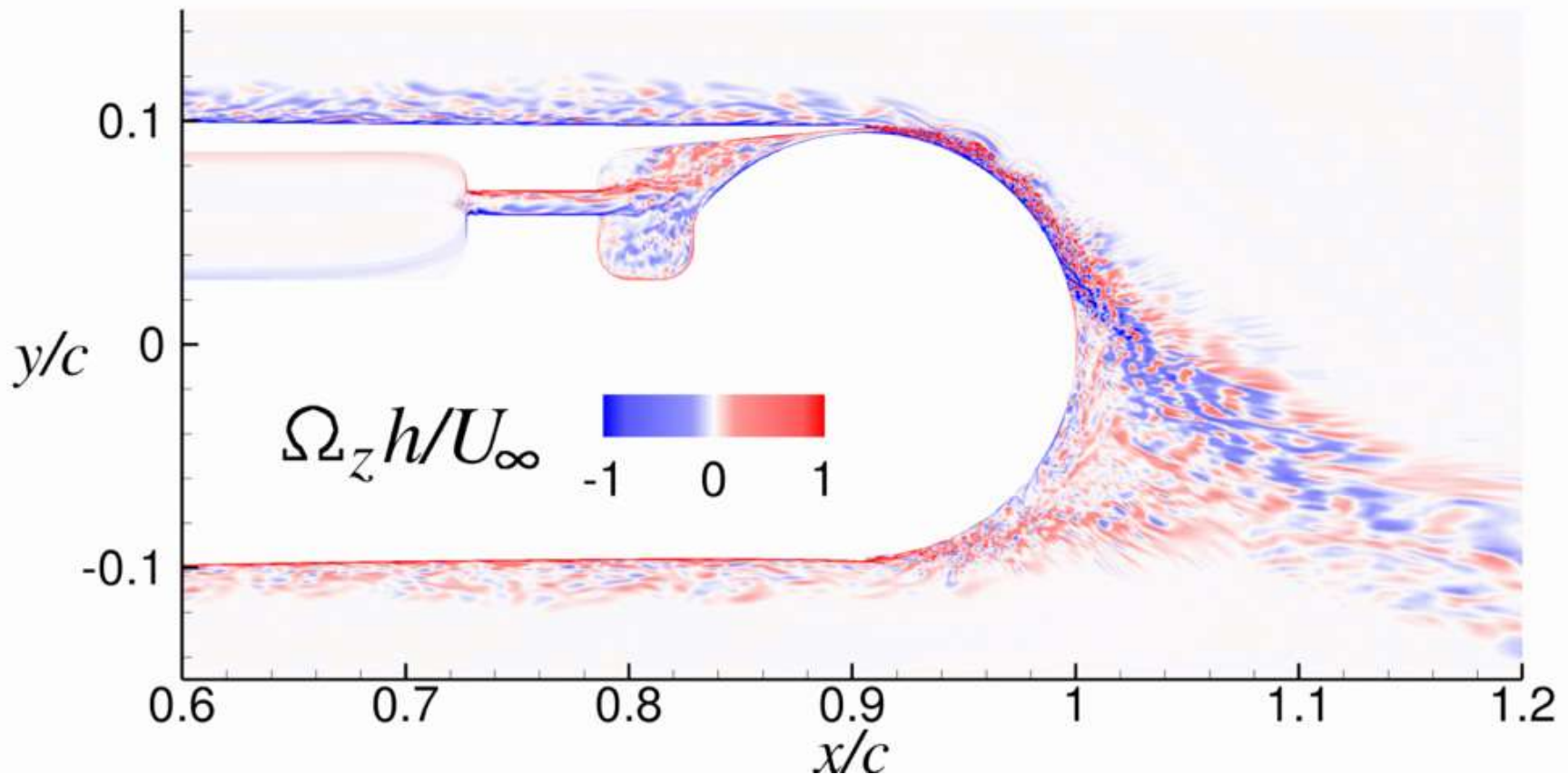
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# LES results: Flow around the airfoil

Instantaneous spanwise vorticity

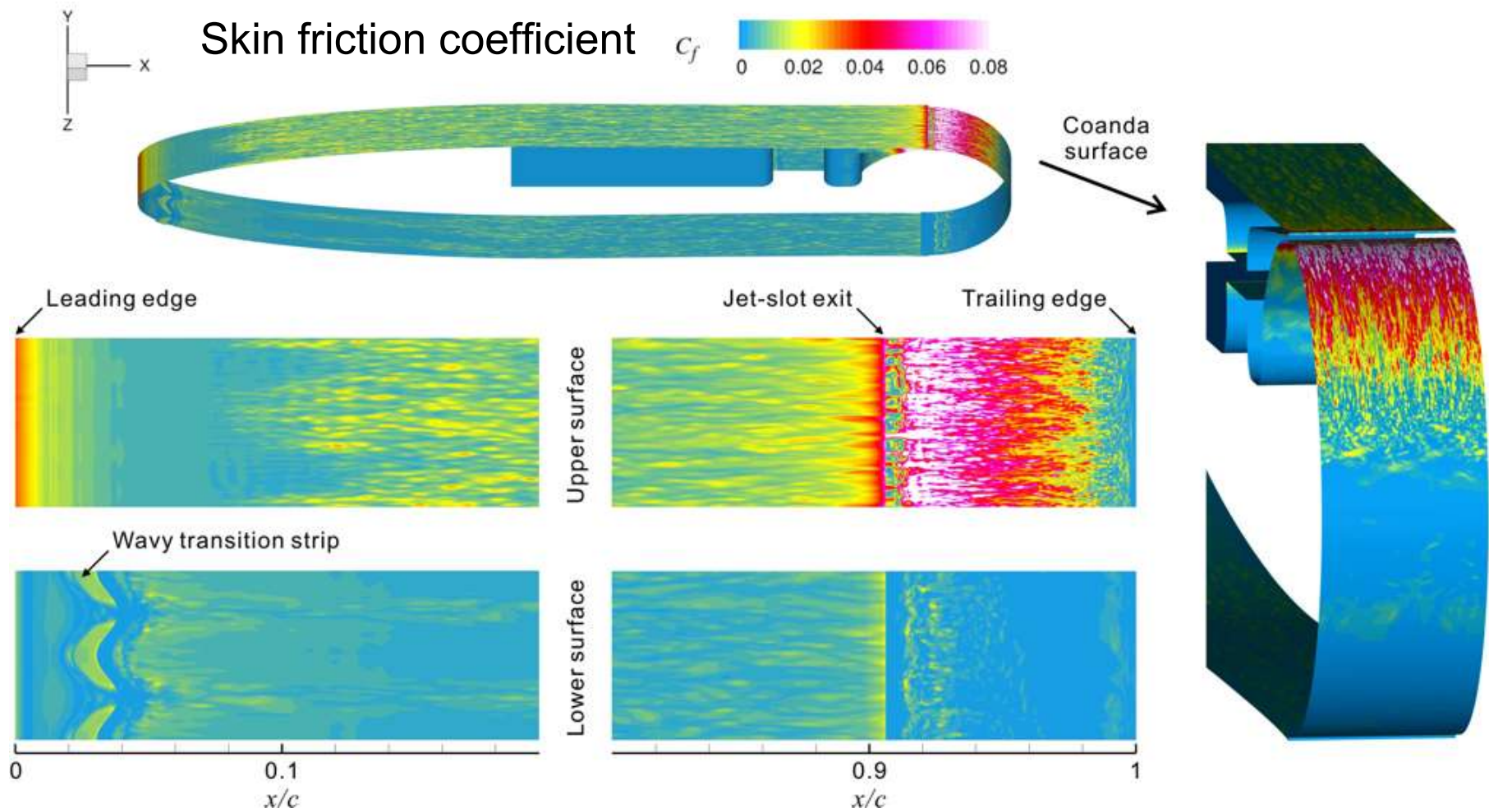


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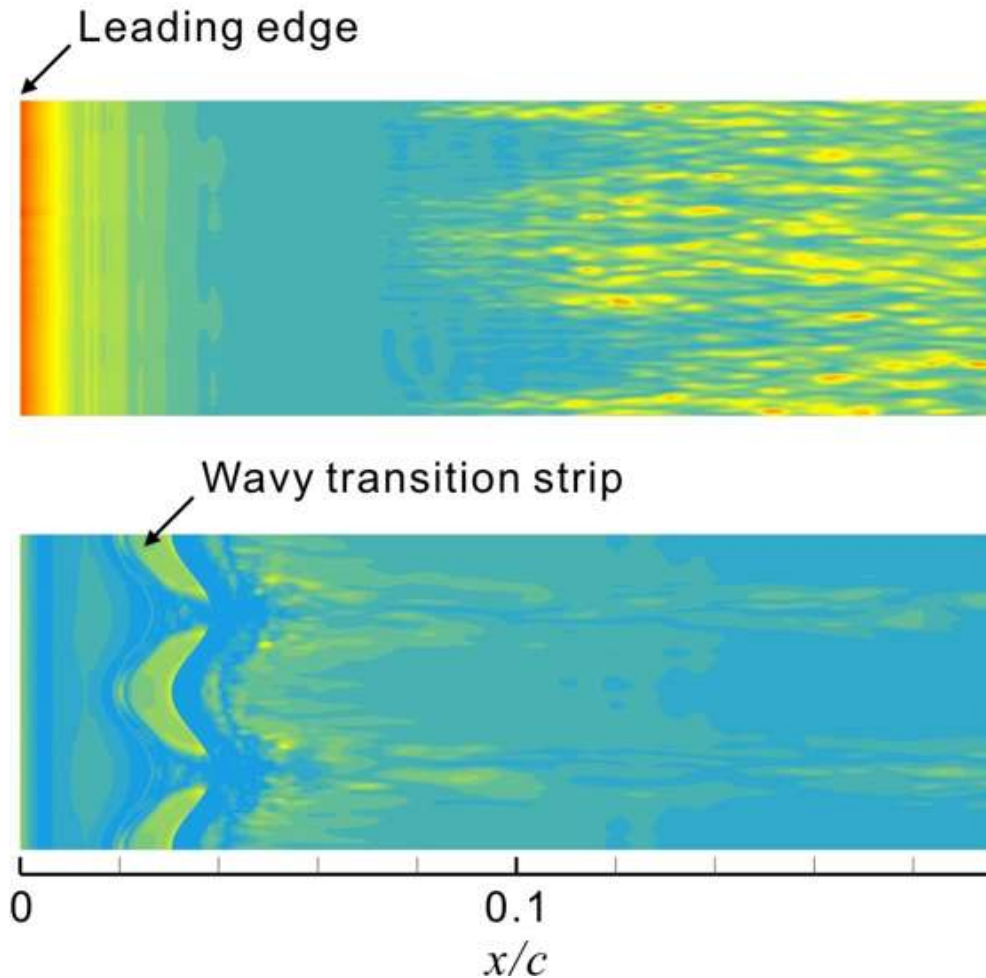
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# LES results: Flow around the airfoil





# LES results: Self-sustained transition



Turbulence was sustained with no “inlet disturbances” given in the present LES (disturbances were given to the whole domain only at the initial stage)

## Upper side

Spanwise modulation



Transition to turbulence sustained around  $x/c = 0.1$

## Lower side

3D separation behind the strip



Transition to turbulence sustained around  $x/c = 0.4$

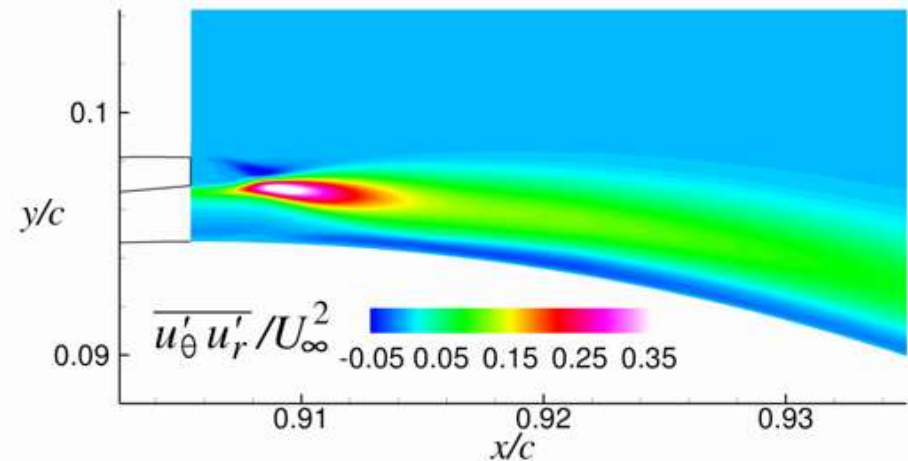
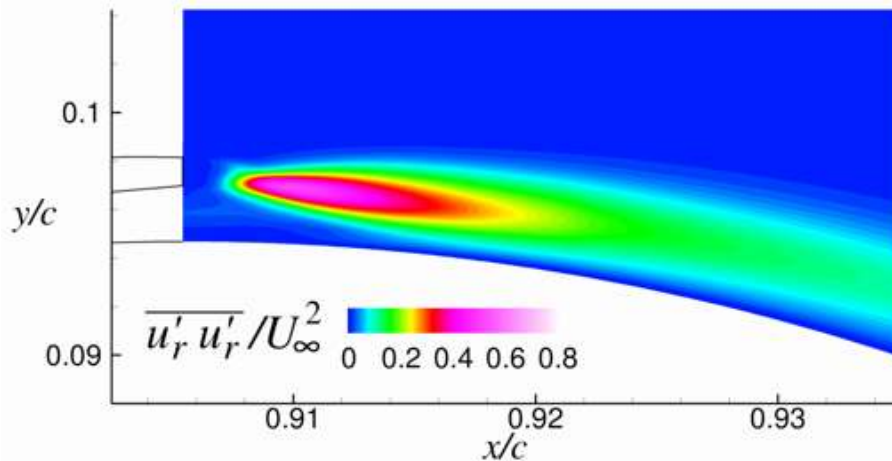
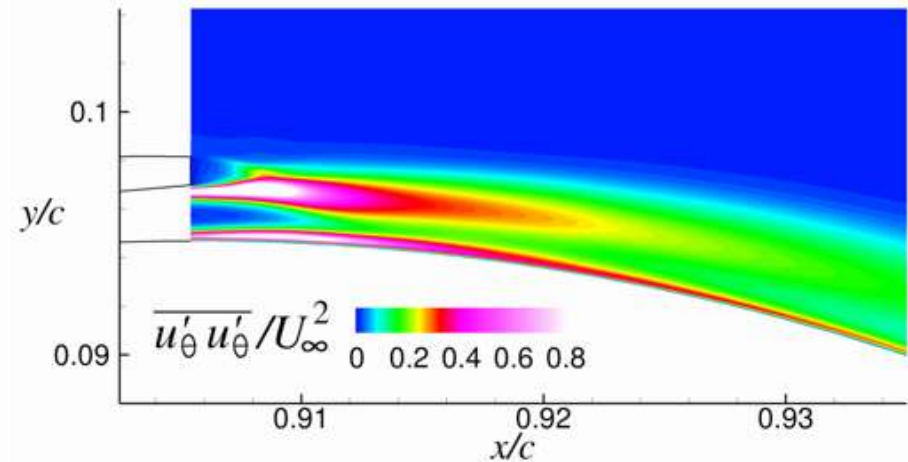
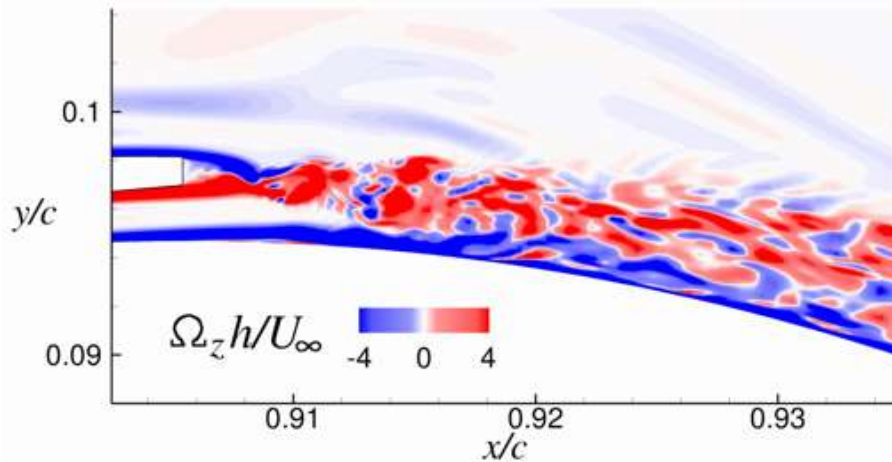


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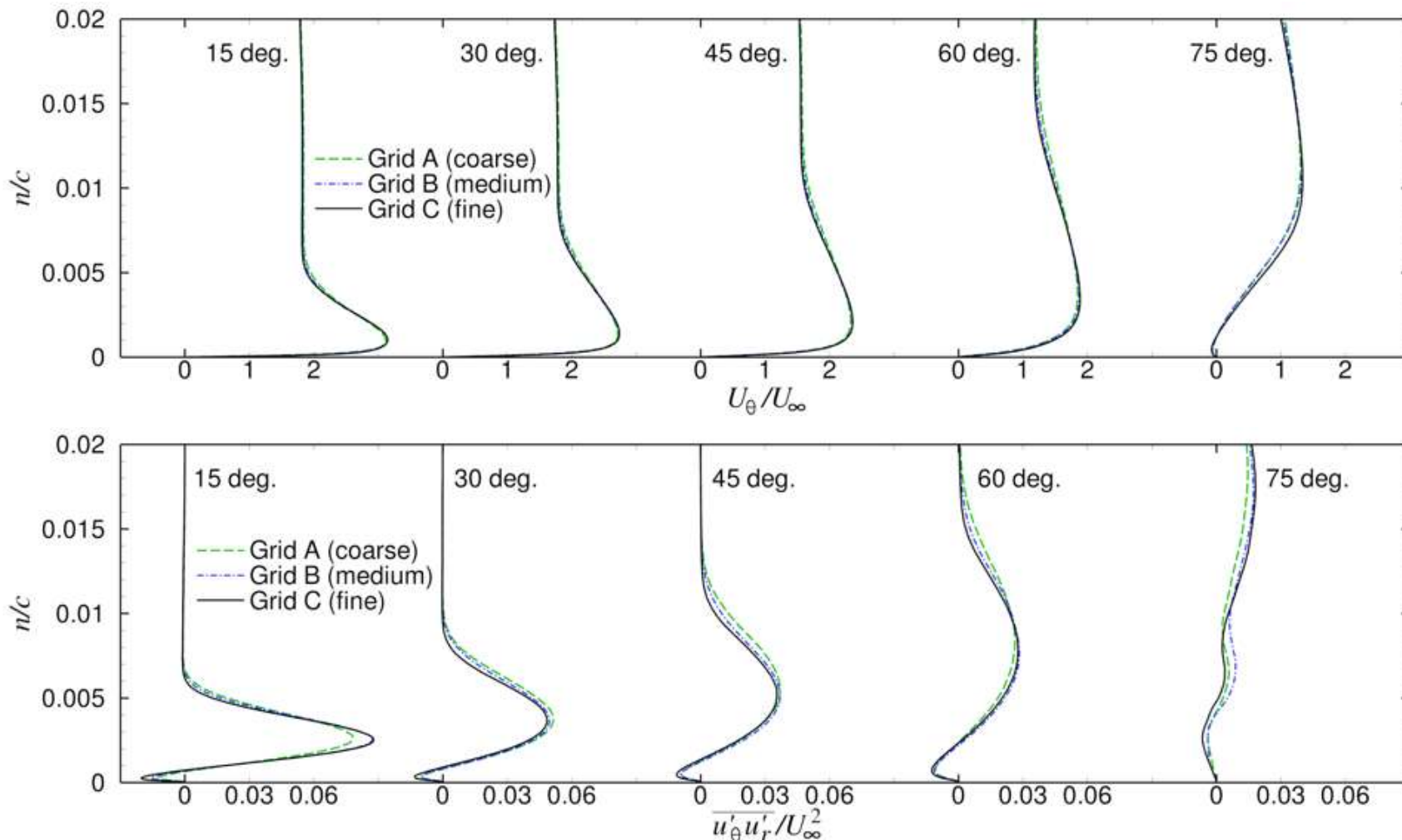
# LES results: Flow around the jet exit





# LES results: Coanda jet profiles

Top: Streamwise velocity  
Bottom: Reynolds shear stress


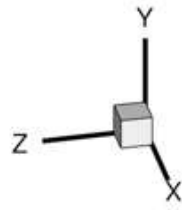
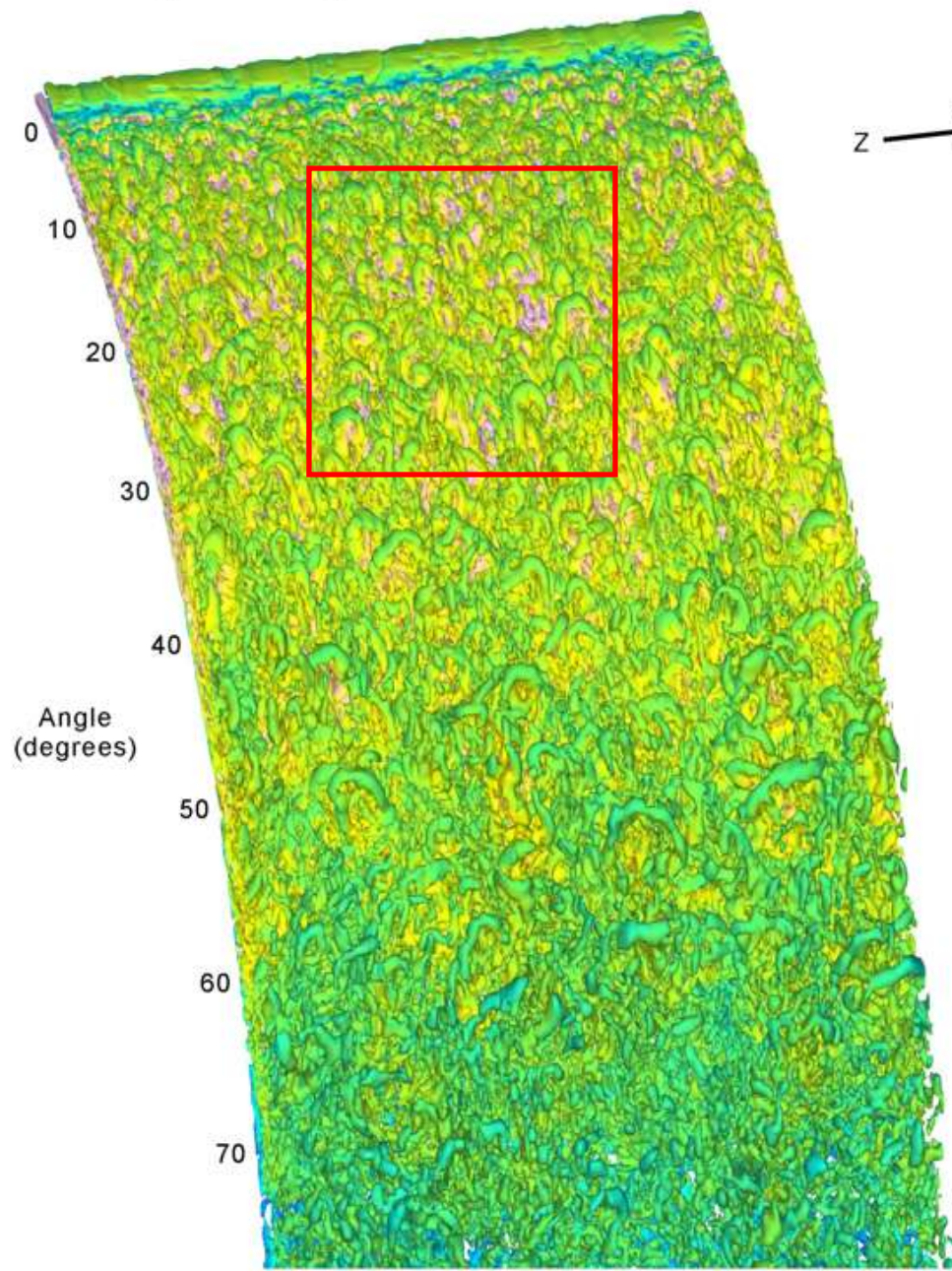


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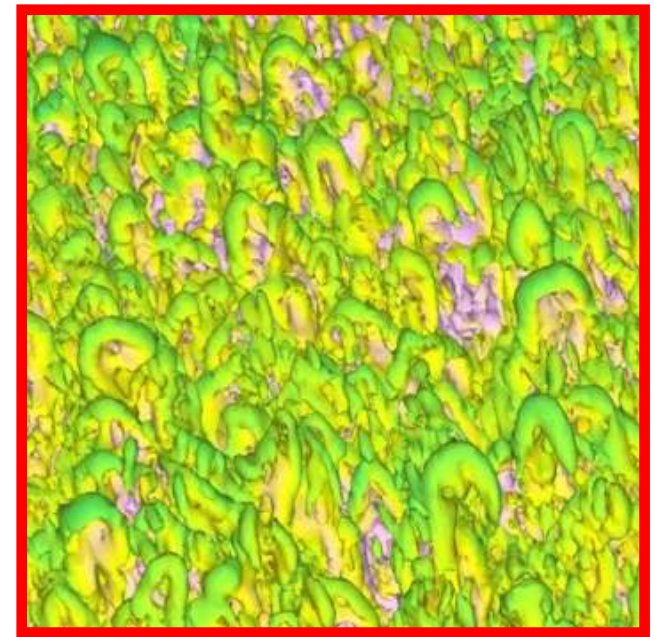
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$(u_i u_i)^{1/2} / U_\infty$

A horizontal color bar ranging from 0 to 3. The color gradient starts with blue at 0, transitions through green and yellow, and ends with red at 3.

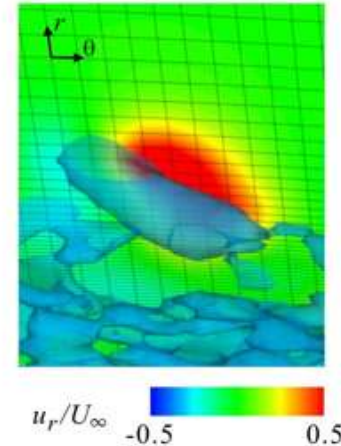
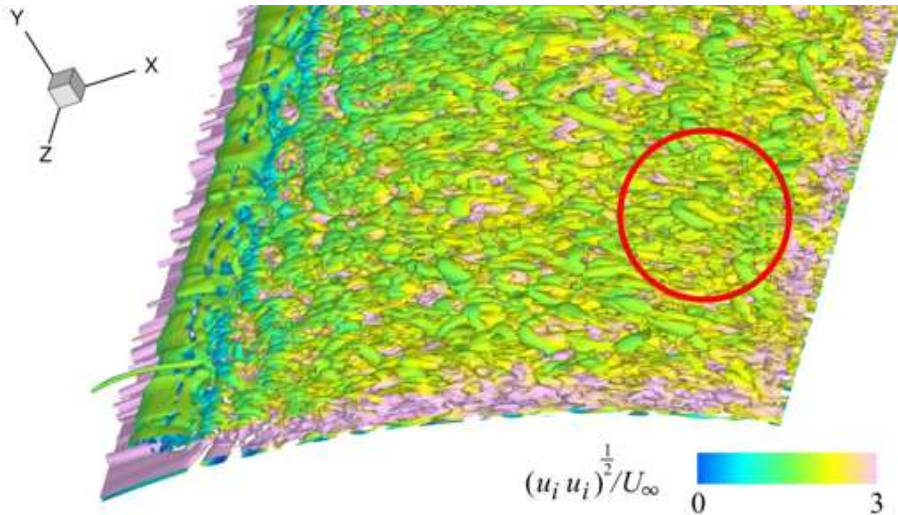
## LES results: Vortical flow structures in the Coanda jet

Isosurfaces of Q  
(2nd Invariant of velocity gradient tensor)  
colored based on velocity magnitude

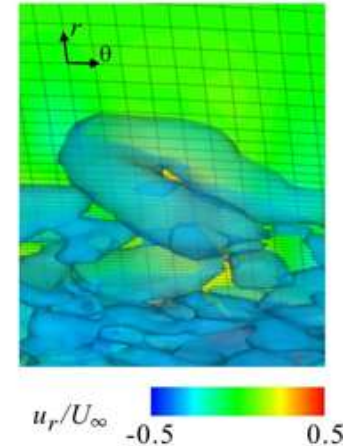




# LES results: Backward-tilted hairpin vortices



Radial (r) velocity  
between the legs



Radial (r) velocity  
outside the hairpin

- Backward-tilted (*i.e.*, head of each hairpin is located upstream of its legs)
- Located above the high-momentum jet flow
- Creating a strong upwash between the legs

→ Lifting the high-momentum flow upward → Turbulent mixing enhanced



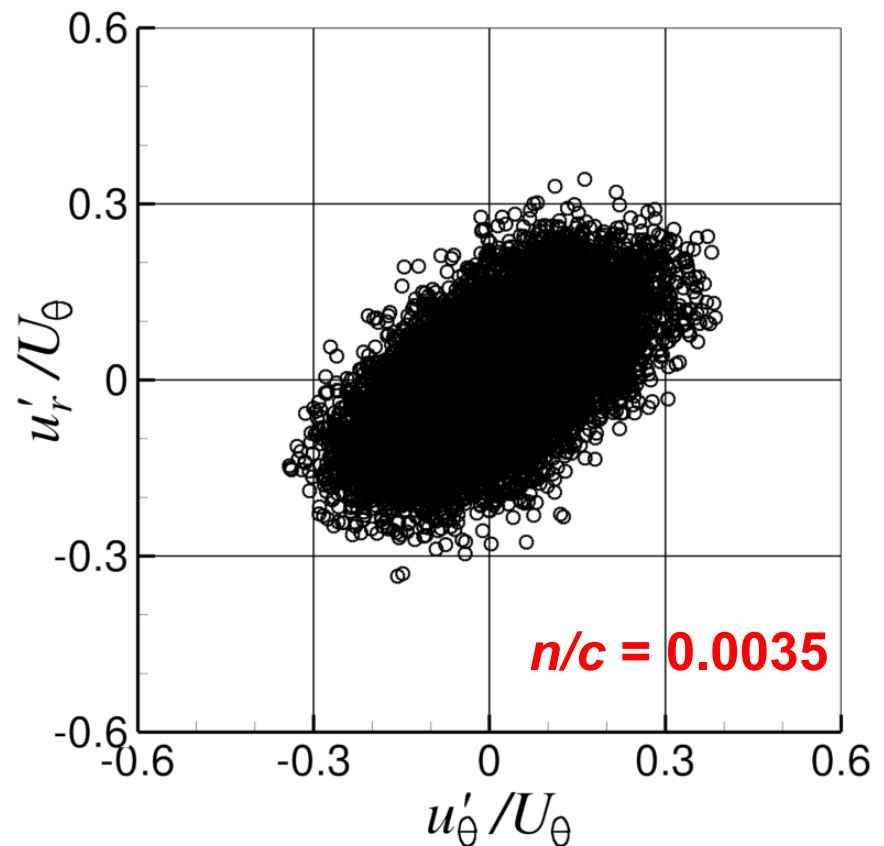
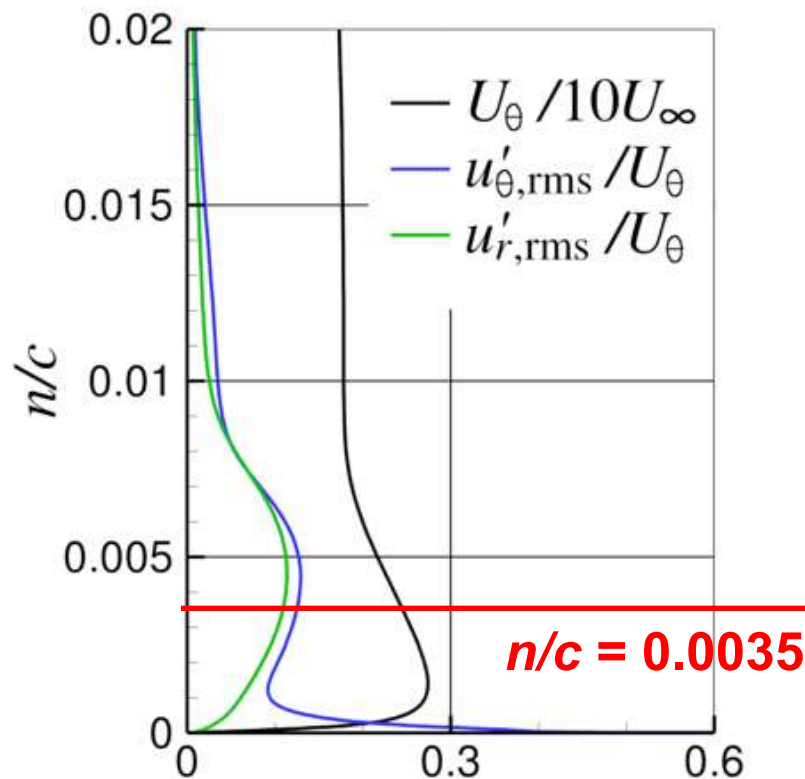
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# LES results: Plots of velocity fluctuations

$\theta = 30$  degrees



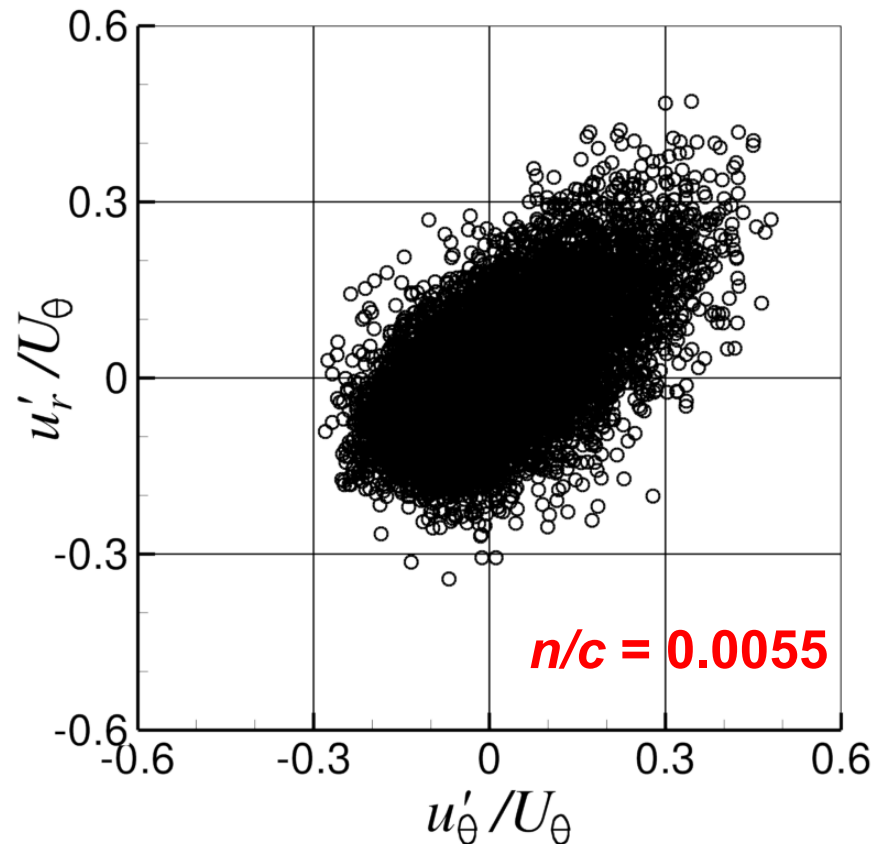
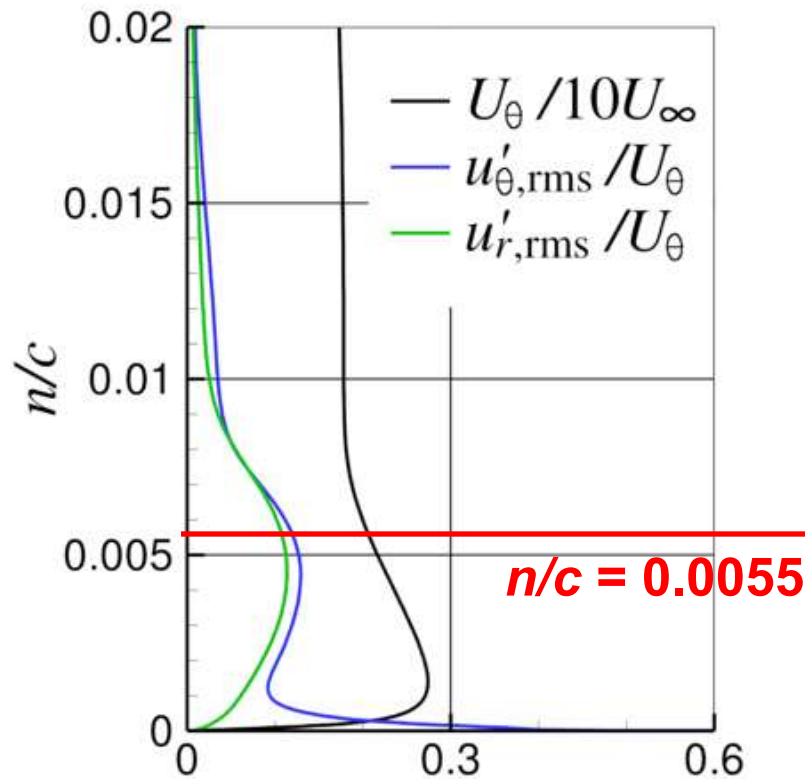
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# LES results: Plots of velocity fluctuations

$\theta = 30$  degrees



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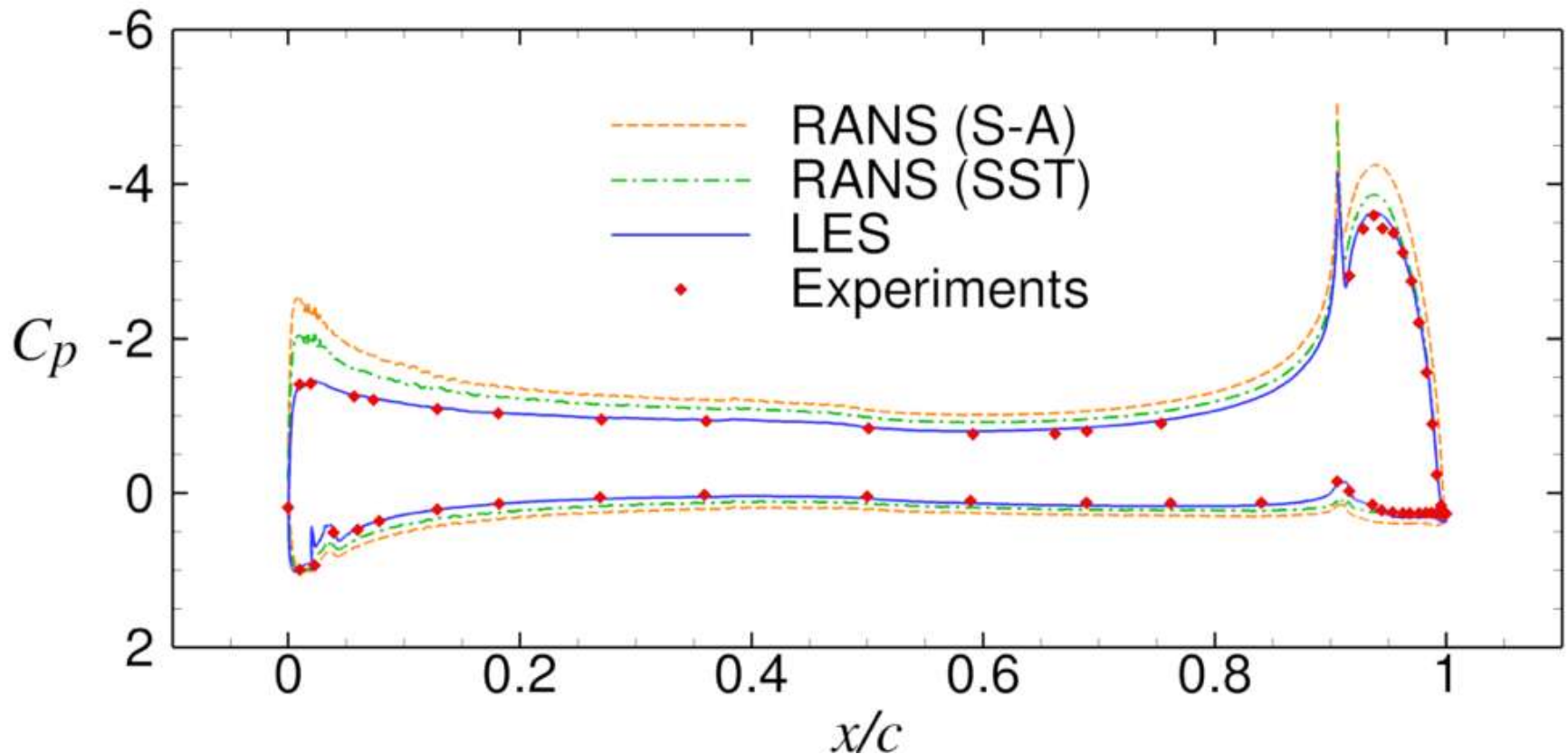
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# Comparisons between LES and RANS

Mean pressure distributions



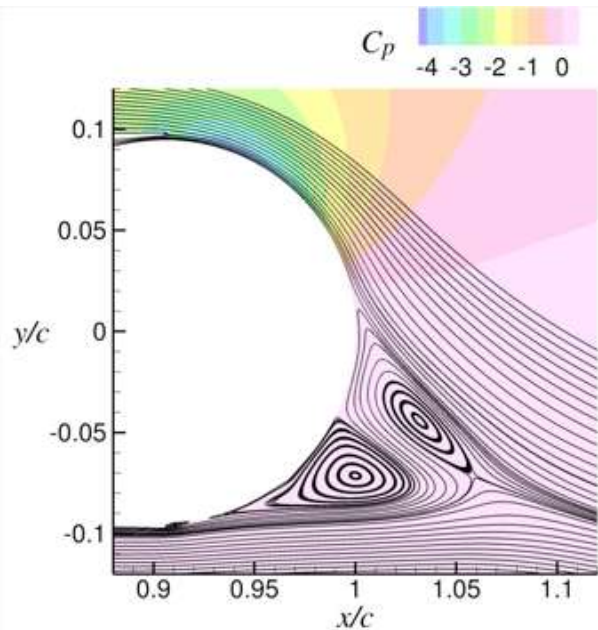
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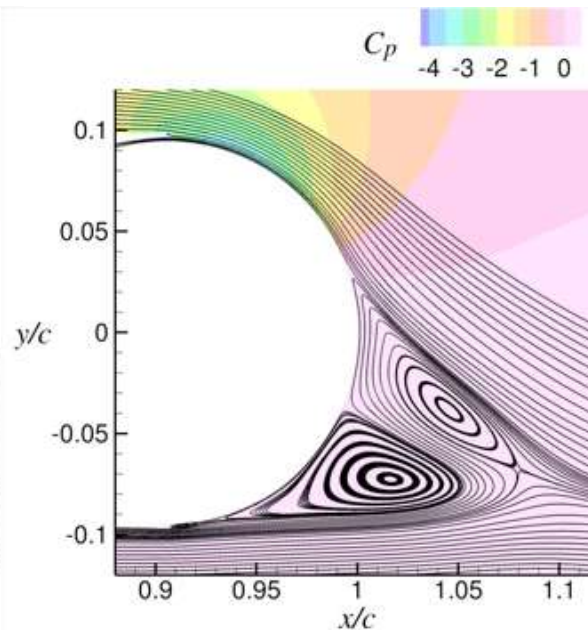
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# Comparisons between LES and RANS

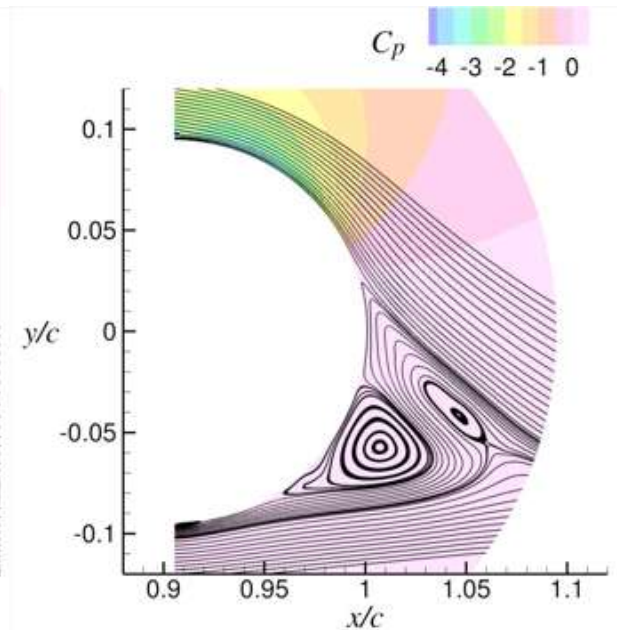
RANS (S-A)



RANS (SST)



LES



Jet separation: 75.0 deg.

Bubble size: 0.058c

Lift coefficient: 1.85

69.0 deg.

0.080c

1.60

69.5 deg.

0.060c

1.36



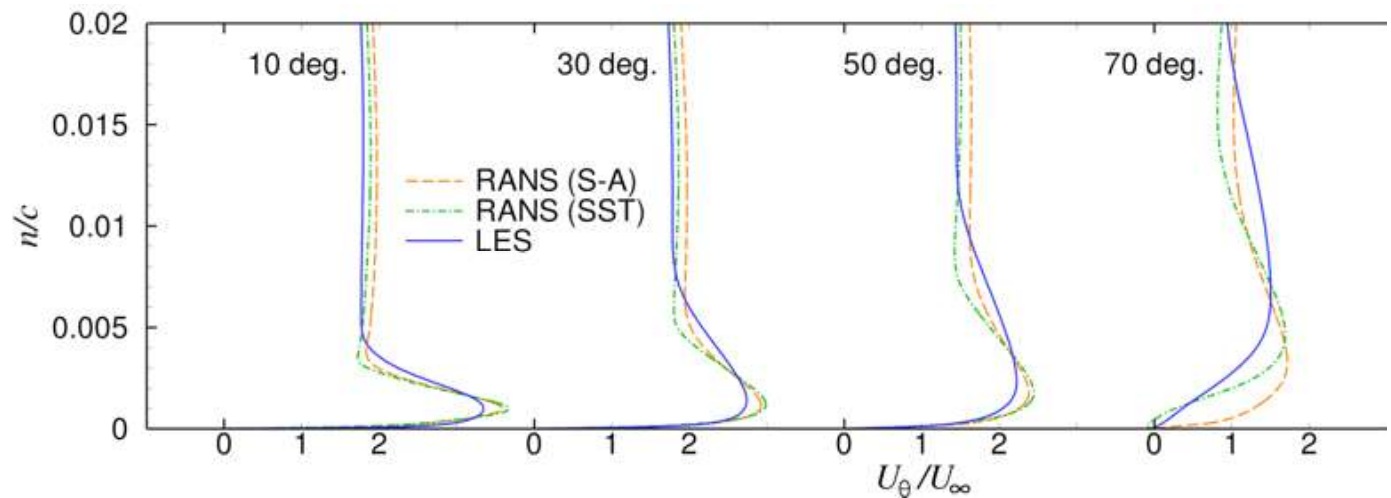
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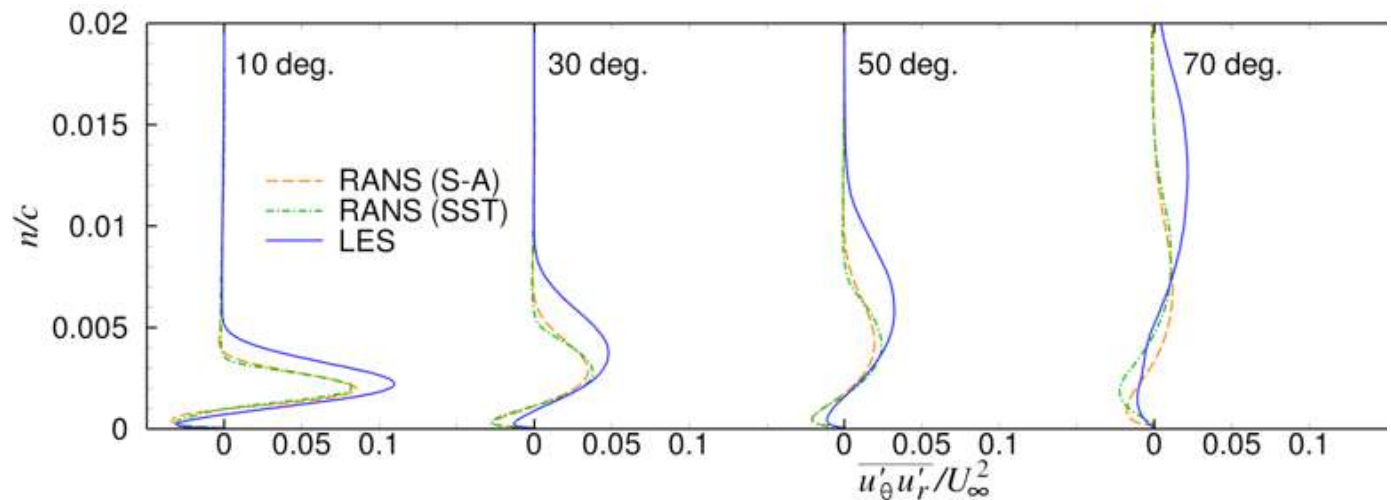
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# Comparisons between LES and RANS

Streamwise  
velocity



Reynolds  
shear stress



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# Conclusions

High-resolution LES of a turbulent Coanda jet (applied to a circulation control airfoil) was performed and was compared with RANS results

## LES results:

1. Pressure distributions agreed well with the preliminary experiments
2. Many “backward-tilted” hairpin vortices were observed in the outer shear layer of the jet; the hairpins lift high-momentum flow upward

## Comparisons between LES and RANS:

3. S-A and SST models predicted a larger circulation and a higher lift, even though SST model predicted a correct jet separation location
4. Both models predicted a smaller jet spreading rate than the LES as the eddy viscosity was too small in the outer shear layer of the jet



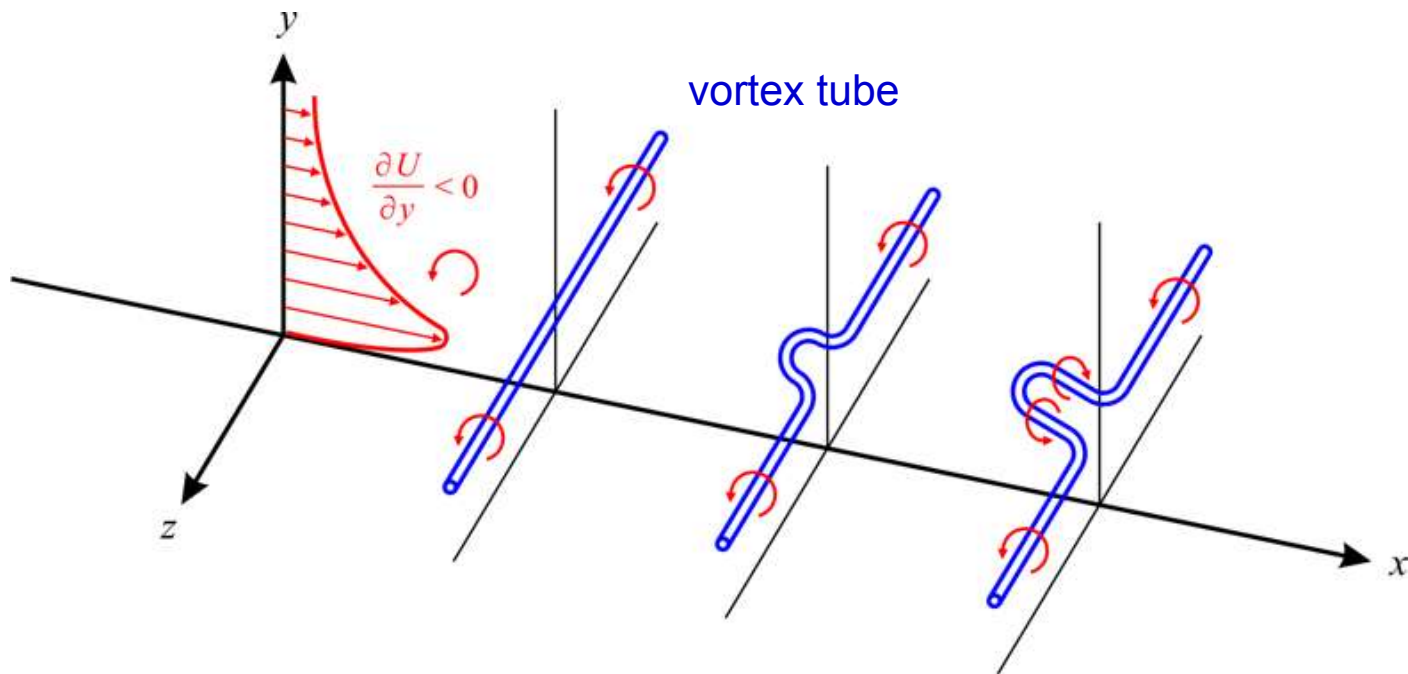
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# (backup slide)



Similar but opposite to “forward-tilted” hairpins in boundary-layer flows

Boundary-layer flows:  $\partial U / \partial y > 0$

Wall-jet flows:  $\partial U / \partial y < 0$



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